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Power parameters of the process of hardening of cylindrical parts by a toroidal roller by the method of surface plastic deformation

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Power parameters of the process of hardening of cylindrical parts by a toroidal roller by the method of surface plastic deformation

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Abstract. A theoretical study of the influence of various technological factors on the force parameters of the hardening process of a cylindrical blank by a method of surface plastic deformation was performed. Based on the approximate model of plastic deformation propagation, an engineering technique has been developed that allows one to specify the force regimes of the surface hardening process with a toroidal roller, taking into account the required degree of deformation of the hardened layer, taking into account the mutual influence of the geometric parameters of the workpiece, the deforming roller and the required depth of cold work. The results of the theoretical study are in good agreement with the known experimental data and can be used in the development of technological operations for hardening machine parts by rolling in rollers or balls.

1. Introduction

Strengthening of parts made of metals and their alloys by the method of surface plastic deformation (SPD) is an effective means of increasing the working life of technological and transport machines [1-11]. Particularly widely used is a surface hardening of shafts and axes by rollers or balls (figure 1). The main technological parameters of the process are the force of plastic deformation, the axial feed of the roller, the depth and degree of deformation of the hardened layer, which is in a rigid relationship with the geometric parameters of the deforming elements and billet [12–15]. Technological processing modes are assigned in accordance with the operating conditions of the part, which ensures the highest hardening efficiency [1–5, 16, 17].

In this case, the degree of deformation of the hardened layer is determined through the geometrical parameters of the residual print or by the relative change in hardness of the workpiece material. In the real conditions of the hardening process, under the contact surface of the roller, a local deformation center is formed in which the material, testing the action of the surrounding volumes, is under conditions of comprehensive uneven compression. Therefore, the force parameters of the hardening process must be determined first of all, depending on the size and shape of the center of plastic deformation.

The aim of the article is to develop an engineering technique that allows one to specify the force regimes of the process of surface hardening of a cylindrical billet by a toroidal roller, taking into account the required degree of deformation of the material, determined taking into account the mutual

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influence of the geometric parameters of the workpiece, the deforming roller and the required depth of cold work.

2. Main provisions and analytical dependencies

Let us consider the process of hardening the outer surface of a cylindrical part with a torus roller (figure 1).

Under conditions of processing with the creation of a local center of deformation, the volume of material experiencing a comprehensive uneven compression is limited by the cone of sliding of the deforming element formed under the contact surface [18, 19].

Construction of slip cones is performed using an approximate model of propagation of plastic deformation [18], in accordance with which lines of the main shear stresses are drawn from the points of the perimeter of the contacting surface, at an angle $\beta = 45^{\circ}$ to the direction of the external compressive force. In the process of hardening, the external compressive forces are directed along the normals to the contact surface of the deforming roller and the workpiece.

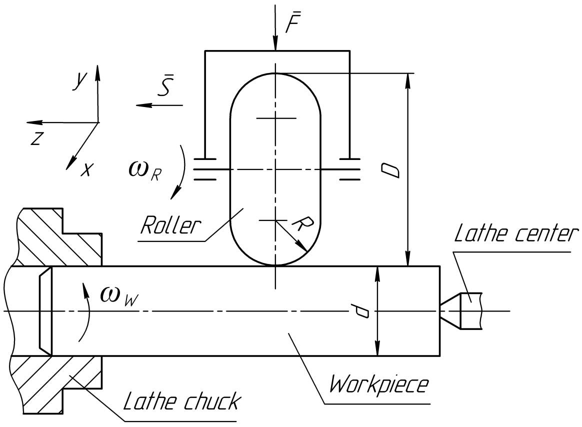

Figure 1. Schematic diagram of hardening of a cylindrical billet by a torus roller: R – profile radius of the roller; D – roller diameter; d – the outer diameter of the hardened workpiece; $\overline{F}$ – force of deformation; $\overline{S}$ – axial feed of roller; ω_W – angular speed of workpiece rotation; ω_R – angular speed of roller rotation.

In the general case, the cone of sliding can be a rather complex figure, because its outlines are completely determined by the shape of the perimeter of the contact surface. The features of the shape of the local focus of deformation arising in the process of hardening in accordance with the proposed procedure are taken into account by considering two sections of the cone of slip located in mutually perpendicular planes yz and xy (figure 2, a, b).

The section of the slip cone in the plane yz (figure 2, a) is obtained by drawing the lines of the main shear stresses through points A and B at an angle β to the direction of the normal $n_1 - n_1$ and $n_2 - n_2$. The figure ABC thus obtained is the cross-section of the slip cone in the plane yz. In this case, the smallest distance from the initial surface of the workpiece to the vertex C of the slip cone h_R will be equal to the depth of propagation of plastic deformation in the plane yz, i.e. depth of work hardening in a given plane.

In the same way, the section of the cone of sliding AEF (figure 2, b) in the plane xy is constructed. In this case, the distance h_D will be equal to the depth of propagation of plastic deformation (depth of cold work) in a given plane.

In general, the degree of deformation is defined as the ratio of absolute strain to the initial size of the deformable element, within which plastic deformation extends.

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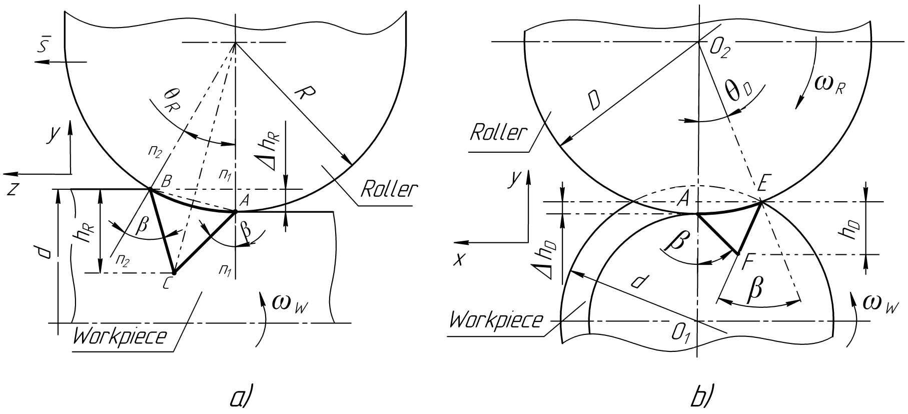


Figure 2. Construction of sections of a cone of sliding: a) section of the slip cone ABC in the plane yz; b) section of the slip cone AEF in the plane xy; Δh_R and Δh_D - the depth of introduction of the roller into the metal of the workpiece in the planes yz and xy; h_R and h_D is the distance from the surface of the workpiece to the vertex of the slip cone in the planes yz and xy; θ_R and θ_D - the angle of contact of the roller with the workpiece in the planes yz and xy; β – the angle of inclination of the lines of the main shearing stresses to the normals of the contact surface (it is assumed in the calculations $\beta = 45^\circ$).

Consequently, the degree of deformation of the hardened workpiece layer is determined as the average value within the deformation center by the formula

$$\varepsilon = \frac{\sum_{i=1}^{n}\left(\frac{\Delta h_i}{h_i}\right)}{n}, \tag{1}$$

where Δh_i is the depth of the roller insertion into the workpiece material in the i section, directed along the normal to the contact surface;

h_i – the depth of propagation of plastic deformation (depth of cold work) in the material of the workpiece in the -the section (equal to the distance from the surface of the workpiece to the vertex of the section of the cone of sliding);

n – the total number of sections in which determined Δh_i and h_i.

Parameters Δh_i and h_i in the equation (1) should be determined to take into account the mutual influence of the geometric parameters of the workpiece, the deforming roller, and the hardening depth.

3. Determination of the degree of deformation of the strengthened metal in the plane yz (figure 2, a)

The depth of embedding the roller in the workpiece in the plane yz

$$\Delta h_R = AB \cdot Sin\frac{\theta_R}{2} = 2R \cdot Sin^2\frac{\theta_R}{2}. \tag{2}$$

The depth of propagation of plastic deformation in the plane yz

$$h_R = BC \cdot Cos(\beta - \theta_R) = R \cdot \frac{Sin\frac{\theta_R}{2} \cdot Sin(\beta + \theta_R)}{Sin\left(\beta - \frac{\theta_R}{2}\right)}. \tag{3}$$

Equation 3 establishes the relationship between the ratio $\frac{R}{h_R}$ and the angle of contact between the roller and the workpiece θ_R in the form (on condition $\beta = 45^\circ$)

$$\frac{R}{h_R} = \frac{Sin\left(45^\circ - \frac{\theta_R}{2}\right)}{Sin\frac{\theta_R}{2} \cdot Sin\left(45^\circ + \theta_R\right)}. \tag{4}$$

After substituting (2) and (3) in (1), we obtain equation for determining the degree of deformation of a strengthened layer in the yz (for $n = 1$ and $\beta = 45^\circ$)

$$\varepsilon_{yz} = \frac{\Delta h_R}{h_R} = \frac{2 \cdot Sin\frac{\theta_R}{2} \cdot Sin\left(45^\circ - \frac{\theta_R}{2}\right)}{Sin\left(45^\circ + \theta_R\right)}. \tag{5}$$

4. Determination of the degree of deformation of the reinforced metal in the plane xy (figure 2, b)

The angle of contact between the roller and the workpiece in the plane xy

$$\theta_D = arccos\left(\frac{\left|O_1O_2\right|^2 + \left(\frac{D}{2}\right)^2 - \left(\frac{d}{2}\right)^2}{2 \cdot \left|O_1O_2\right| \cdot \left(\frac{D}{2}\right)}\right), \tag{6}$$

where $\left|O_1O_2\right| = \frac{D}{2} + \frac{d}{2} - \Delta h_R$ is the distance between the axes of rotation of the roller and the workpiece.

The depth of propagation of plastic deformation in the workpiece material in the plane xy (figure 2, b) is determined by the equation

$$h_D = \frac{D}{2} \cdot \frac{Sin\frac{\theta_D}{2} \cdot Sin\left(\beta + \theta_D\right)}{Sin\left(\beta - \frac{\theta_D}{2}\right)}. \tag{7}$$

The depth of introduction of the deforming roller into the workpiece material in the plane xy

$$\Delta h_D = AE \cdot Sin\frac{\theta_D}{2} = D \cdot Sin^2\frac{\theta_D}{2}. \tag{8}$$

After substituting (7) and (8) in (1), we obtain equation for determining the degree of deformation of a hardened layer in the (for $n = 1$ and $\beta = 45^\circ$)

$$\varepsilon_{xy} = \frac{\Delta h_D}{h_D} = \frac{2 \cdot Sin\frac{\theta_D}{2} \cdot Sin\left(45^\circ - \frac{\theta_D}{2}\right)}{Sin\left(45^\circ + \theta_D\right)}. \tag{9}$$

Finally, the degree of deformation of the strengthened material in the slip cone (deformation center) is determined in accordance with equation (1) as the arithmetic mean over the two planes yz and xy

$$\varepsilon = \frac{\varepsilon_{yz} + \varepsilon_{xy}}{2} \cdot 100\% . \tag{10}$$

The accuracy of determining the degree of deformation of the strengthened layer by equation (10) will increase if the total number of cross sections in which Δh_i and h_i are determined is increased.

5. Determination of the deformation force

In this article, the deformation force F necessary for surface hardening is determined by a simplified procedure, in accordance with which the working toroidal surface of the roller is replaced by the equivalent surface of the ball (figure 3).

With an accuracy sufficient for engineering calculations, it is assumed that the contact pressures on the working surface of the ball are equal to the resistance of deformation of the workpiece material, taking into account hardening. Taking into account this assumption, the plastic deformation force is determined by the equation

$$F = \sigma_s \cdot A_b , \tag{11}$$

where $A_b = \frac{\pi \cdot D_b \cdot \Delta h_b}{4}$ is the area of the contact surface of the ball and workpiece, mm^2,

$D_b = \sqrt{D \cdot 2R}$ is the diameter of the ball;

$\Delta h_b = D_b \cdot Sin^2 \frac{\theta_b}{2}$ is the depth of ball penetration into the workpiece material,

$\theta_b = \sqrt{\theta_R \cdot \theta_D}$ is the contact angle of the ball with the surface of the workpiece;

$\sigma_s = \sigma_{0,2} + g \cdot \varepsilon^b$ is the resistance of deformation of the material of the workpiece taking into account hardening, MPa,

$\sigma_{0,2}$ is the conditional yield point of the material of the initial workpiece;

g and b – the empirical coefficients of hardening of the workpiece material;

ε – the degree of deformation of the material when hardened by a ball, determined in accordance with equation 10.

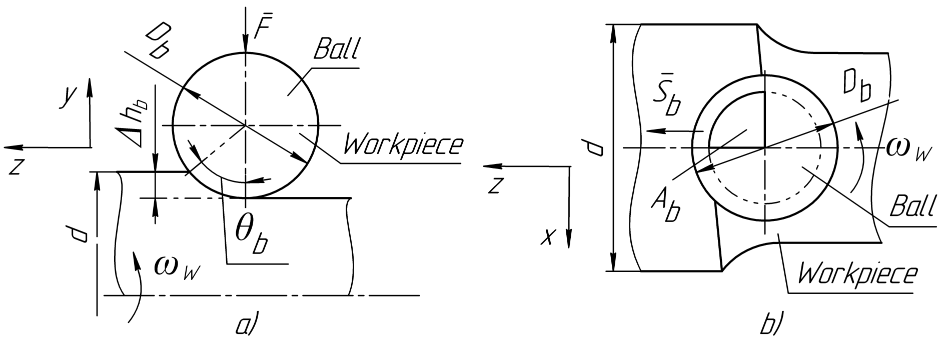


Figure 3. Schematic diagram of the process of hardening the cylindrical blank with a ball: a) in the plane yz; b) in the plane xz

6. Construction of graphical dependencies and practical application of the developed methodology

Initial data for calculating the strength parameters of the hardening process:

- workpiece material;
- d – the outer diameter of the initial workpiece;
- h – the required depth of the hardened workpiece layer (depth of work hardening).

In the presented article, calculations are performed for steel 45 in a normalized state having the following mechanical characteristics [20]: $\sigma_{0,2} = 35\frac{kgf}{mm^2}$, $g = 8,66\frac{kgf}{mm^2}$, $b = 0,48$.

The diameter of the initial workpiece $d = 70$ mm.

In engineering calculations, the depth of cold work is usually determined by empirical dependence

$$h = K_d \cdot d \tag{12}$$

where K_d is the coefficient of relative depth of the hardened layer.

According to the results of fatigue tests [16], it is recommended to take $0,01 \le K_d \le 0,05$, in [12] the best results were obtained when $K_d = 0,5...0,7$ a range was established in $0,02 \le K_d \le 0,1$ [1]. Based on the recommendations given for the given workpiece diameter $d = 70$ mm, the required hardening depth is adopted $h = h_R = 5$ mm.

The depth of propagation of plastic deformation is determined by the greatest distance from the surface of the workpiece to the vertex of the slip cone in the sections considered. Therefore, it is of interest to establish a relationship between dimensions h_R and h_D in the entire range of the parameters considered. To this end, the coefficient of change in the height of the slip cone K_h is determined in the form

$$K_h = \frac{h_R}{h_D} \tag{13}$$

Analysis of the graphical dependences of the coefficient K_h change on the parameters $\frac{R}{h}$ and D (figure 4) shows that the depth of propagation of plastic deformation in the plane yz is always greater than in the plane xy. Therefore, in this case, the parameter h must be assigned, guided by the depth of propagation of plastic deformation in the plane yz (i.e., adopted $h = h_R$), which was done in the presented study.

From the analysis of graphical dependencies (figure 5) it is seen that the degree of deformation of the hardened layer rises to the maximum value at an angle $\theta_R = 45^\circ$. At the same time, the greatest degree of deformation in the hardening process is achieved when the roller is treated with a smaller ratio value $\frac{D}{d}$.

In accordance with the graph in figure 6, for any value of the contact angle parameter $\frac{D}{d}$, a ratio $\frac{R}{h} \approx 1$ corresponds to $\theta_R = 45^\circ$. Thus, from the analysis of the graphical dependencies shown in figure 5 and figure 6, it follows that the greatest degree of deformation of the reinforced layer can be ensured during the roller treatment with the ratio $\frac{R}{h} \approx 1$.

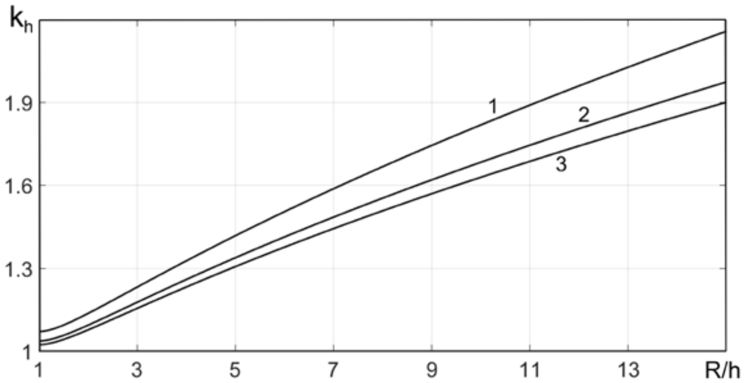


Figure 4. Dependence of the coefficient K_h on the ratio $\frac{R}{h}$: 1 – $\frac{D}{d}=\frac{5}{7}$; 2 – $\frac{D}{d}=\frac{10}{7}$; 3 – $\frac{D}{d}=\frac{15}{7}$; $h=5$ mm ; $d=70$ mm

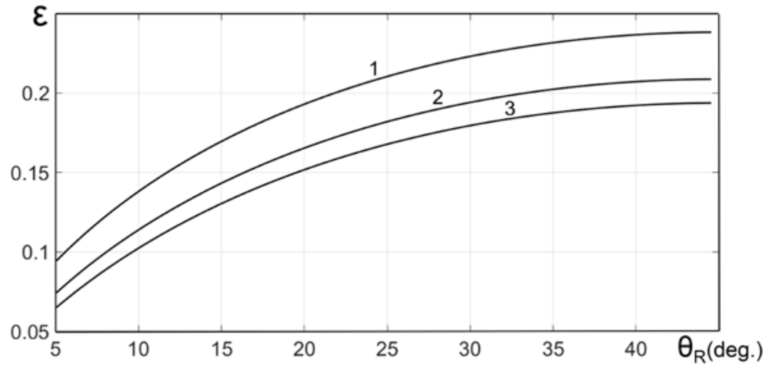


Figure 5. Dependence of the degree of deformation ε of the hardened layer on the angle of contact of the roller with the workpiece θ_R: 1 – $\frac{D}{d}=\frac{5}{7}$; 2 – $\frac{D}{d}=\frac{10}{7}$; 3 – $\frac{D}{d}=\frac{15}{7}$; $h=5$ mm ; $d=70$ mm

Using the developed technique presented by equations (1) - (15), the effect of the parameters $\frac{R}{h}$ and $\frac{D}{d}$ on the degree of deformation ε that can be provided in the hardened layer during roller treatment is analyzed. Analysis of the graphical dependencies (figure 7, a) shows that with decreasing parameters $\frac{R}{h}$ and $\frac{D}{d}$, the degree of deformation of the strengthened layer is increased.

Within the range of the parameter $\frac{D}{d}$ variation, the greatest degree of deformation is achieved by a roller having a profile radius R value of approximately h (i.e. $\frac{R}{h}\approx 1$). To each value of the parameter $\frac{D}{d}$, there corresponds its own value of the greatest degree of deformation, which we call the limit and denote it $\varepsilon_{\max}$. For example, when processing a roller having parameters $\frac{D}{d}=\frac{5}{7}$ and $\frac{R}{h}\approx 1$ the limiting degree of deformation $\varepsilon_{\max}\approx 0,24$. This degree of deformation can be ensured in one pass of the roller.

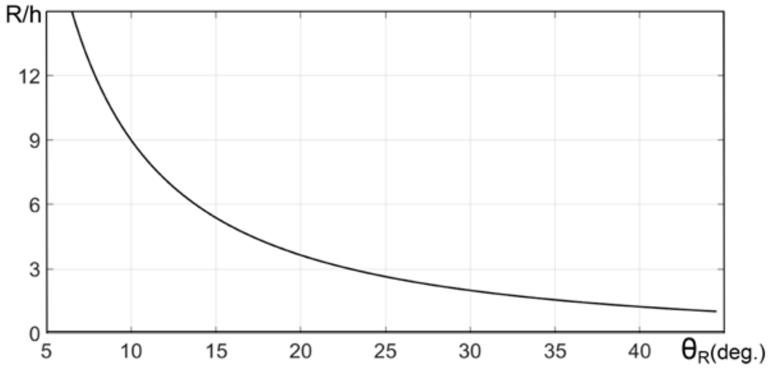
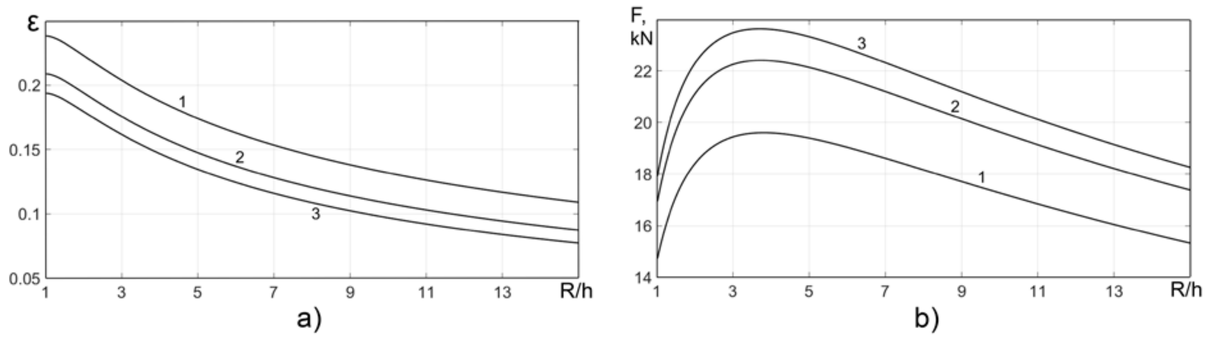


Figure 6. Dependence of the ratio $\frac{R}{h}$ on the contact angle of the roller with the workpiece θ_R for any values of the parameter $\frac{D}{d}$; $h = 5$ mm ; $d = 70$ mm

Provide the required value of the degree of deformation can be due to the application of an appropriate deformation force F. The figure 7, b shows graphical dependencies, which allow assigning the deformation force depending on the parameters $\frac{R}{h}$ and $\frac{D}{d}$. The required deformation force has a maximum at the parameter values $\frac{R}{h} \approx 3{,}5$.



Figire 7. Dependence of the degree of deformation of the hardened layer and the deformation force F on the ratio $\frac{R}{h}$: a) dependence $\varepsilon - \frac{R}{h}$; (b) dependence $F - \frac{R}{h}$; 1 – $\frac{D}{d} = \frac{5}{7}$; 2 – $\frac{D}{d} = \frac{10}{7}$; 3 – $\frac{D}{d} = \frac{15}{7}$; $h = 5$ mm ; $d = 70$ mm

Exceeding the actual deformation force above the theoretical value (figure 7) will cause excessive deformation and, consequently, a decrease in the quality of the finished product.

7. Conclusions

The presented engineering technique allows to assign force regimes of surface hardening of a cylindrical part by a roller taking into account the required degree of deformation of the hardened layer, determined taking into account the mutual influence of geometrical parameters of the workpiece, the deforming roller and the necessary depth of cold work.

The obtained analytical and graphical dependences are in good agreement with the known experimental data [1, 3, 4, 11] and can be used in designing the processes of hardening of shafts and axes by a roller or a ball.

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